DENSITIES, POROSITIES AND MAGNETIC SUSCEPTIBILITIES OF METEORITIC LUNAR SAMPLES: EARLY RESULTS.
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Introduction: Data on the Moon's gravity and topography, as provided by missions such as Lunar Prospector, Kaguya and Lunar Reconnaissance Orbiter, constrain our understanding of the Moon's internal structure. To interpret this flood of data in order to understand the Moon's interior, it is necessary to develop a comprehensive database of lunar rock densities and porosities. Very few measurements of lunar rock porosity or hydrostatic density measurements exist in the literature.

In [1] we reported porosity measurements of five Apollo lunar samples and three lunar meteorites from institutional collections. Subsequently the database has expanded to contain grain densities for 24 additional meteorites, of which 16 have measured porosities. This expanded database allows us to further explore density and porosity trends according to various geological types.

Measurement: Our methods, which are fast, non-destructive and non-contaminating, are outlined in [2]. Grain density is measured by helium ideal-gas pycnometry. Bulk density is measured by the glass bead method developed by [3]. We used beads of average diameter 750 µm, large enough to be easily seen by the unaided eye and removed easily from the sample after completion of measurement. Porosity is calculated directly from bulk and grain densities: $P = 1 - \left(\rho_{bulk}/\rho_{grain}\right)$. The small atomic radius of helium allows it to diffuse rapidly along microfractures and grain boundaries, thus providing the best possible determination of grain density and subsequently porosity. In contrast, prior measurements of porosity in lunar samples (e.g. [4]) typically required immersion of samples in toluene, which might not fully penetrate pore space and thus would underestimate porosity (as well as risk sample contamination). We also measure magnetic susceptibility. Magnetic susceptibility is measured with a handheld SM-30 magnetic susceptibility meter, and corrected for sample geometry according to the calibration by [5].

Basalts: All basalts in this study so far are low-Ti (1-5 wt% TiO_2). They group tightly in grain density (averaging 3.31 ± 0.06 g cm^{-3}) and magnetic susceptibility (log χ = 2.89 ± 0.08) [Fig. 1]. Porosities range from essentially zero to 10%, averaging 5.6%. There is no discernible difference between the two Apollo basalts (12051 and 15555) and the five basaltic meteorites taken as a whole.

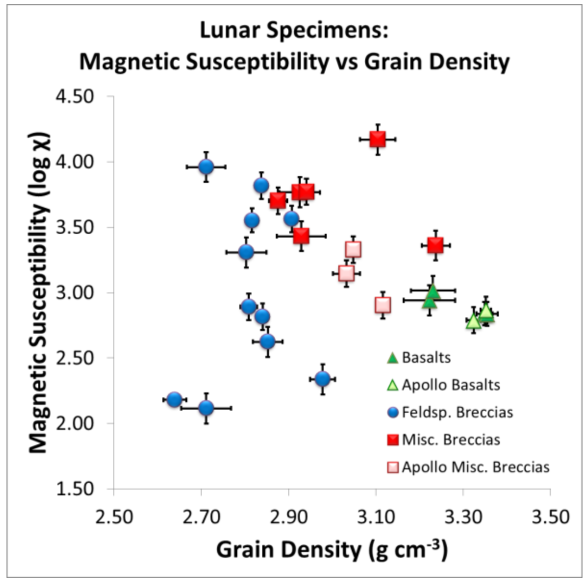

Fig. 1: Grain density vs. magnetic susceptibility for lunar specimens in this study.

Among the meteorites represented here is Northwest Africa (NWA) 4898, which is the first high-Al, low-Ti lunar basalt for which physical properties have been measured. Its lower-than average grain density (3.23 g cm^{-3}) reflects the higher than typical abundance of low density plagioclase in this high aluminum basalt.

Feldspathic Breccias: The feldspathic breccias in this study are all meteorites. Grain densities averaged 2.78 ± 0.11 g cm^{-3}. Magnetic susceptibilities varied over a wide range, from log χ = 2.1 to 4.0. Porosities were low, with all but one (Dhofar 910, P = 12.4% ± 3.3%) below 6.1% porous.

These samples represent a mix of regolith breccias, fragmental breccias, and impact-melt breccias. Of these, impact-melt breccias have substantially lower porosities on average than the others. All but one of the impact-melt breccias in this study had effectively zero porosity, and the exception was within two sigma of zero porosity. Furthermore, on average, the impact-melt breccias had marginally higher magnetic susceptibilities. Shock-induced annealing and compression can account for the first effect, and also can account for the

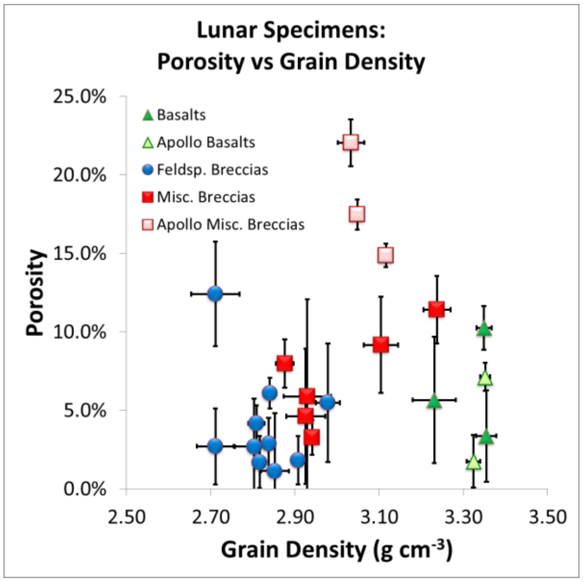

Fig. 2: Porosity vs. Grain Density for lunar specimens in this study. Note that the three Apollo breccias have higher porosities than any of the meteorites.

latter due to shock-induced production of metallic particles [6].

Other Breccias: Also in our database are 10 additional meteorites and 3 brecciated Apollo samples. These represent a range of lithologies and occupy a different range of density and magnetic susceptibility than the basalts or feldspathic breccias [Fig. 1]. While the meteorites in this group have low porosities sharing a range with the felsdpathic breccias and basalts, the Apollo breccias are all above ~15% porosity, making them more porous than any of the meteorites in the study [Fig. 2]. Two of the Apollo stones, both crystalline-matrix breccias, came from the Fra Mauro region of Apollo 14 and are samples of Imbrium basin ejects, but the third (an anorthositic norite) came from the Apennine basin rim near the Apollo 15 landing site. A more detailed discussion of results for these stones was presented in [1]. The difference in porosities suggests a possible difference between lunar meteorite breccias and in-situ surface breccias, perhaps due to ejection-related effects. This difference begs further study.

Among the meteorites in this group are NWAs 773, 2977, and 3160, which are paired but which exhibit substantially different lithologies. The only physical property measured for NWAs 2977 (an olivine gabbro) and 3160 (primarily basaltic) is grain density. Despite the mineralogical differences between the stones, they are similar in grain density, with all stones within 0.08 g cm^{-3} of the average grain density of 3.24 g cm^{-3}.

Discussion: The research presented here represents a significant improvement in our understanding of the density, porosity and magnetic susceptibility of lunar materials. The 16 meteorites with porosity measurements constitute nearly one quarter of the known lunar meteorites.

The difference in porosity between Apollo and meteorite breccias is intriguing and was also noted by Warren [7] in a point counting study on thin sections. Understanding this difference is cause for further study, particularly as a necessary step in understanding the porosity of lunar crust. Three possible explanations other than mere coincidence present themselves. First is a selection effect due to survivability of stones ejected from the lunar surface. Higher-porosity stones may have less chance of surviving the high energies involved. Second, lunar meteorites likely originated from much deeper in the lunar crust, where they may simply have been more compacted from the start. Third, shock from the ejection event itself may have compacted the meteorites and further filled in pore space through shock-induced veining. All three possibilities are likely to contribute to the observed difference, but distinguishing which one dominates and to what degree is important.

As the title of this abstract suggests, what have been presented here are early results of an ongoing study. Much work still remains to be done. In the next few years, the database of lunar material porosities should expand considerably. This will include both meteorites and Apollo samples. Expanding the database of Apollo samples will help address the porosity of in-situ breccias as opposed to meteorite breccias. It will also fill in missing data with the inclusion of thus-far unrepresented high-Ti (9-14 wt% TiO_2) basalts as well as expanding the representation of low-Ti basalts.

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